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A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies—Part I: Methodology

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ABSTRACT

A clear consensus exists in the German society that renewable energies have to play a dominant role in the future German energy supply system. However, many questions are still under discussion; for instance the relevance of the different technologies such as photovoltaic systems and wind energy converters installed offshore in the North Sea and the Baltic Sea. Also concerns exist about the cost of a future energy system mainly based on renewable energies. In order to be able to address the raised issues on a scientifically sound basis we have set up a new simulation model REMod-D (Renewable Energy Model-Deutschland) that models the energy balance of the electricity and heat sector including all renewable energy converters, storage components and loads for a future German energy system for a whole year based on an hourly energy balance. The target energy systems modeled use a high fraction up to 100% of renewable energies to cover the electricity and heat demand (heating and hot water). The model includes also energy retrofit of buildings as a measure to reduce future heat loads of the building sector. A mathematical–numerical optimizer is applied in order to identify system configurations with minimal overall annual cost. In this first part of a two-paper series we describe the methodology of the REMod-D model and discuss cost and performance values of all included components and in the second part we will discuss the results.

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1. Introduction

In the summer of 2011 the German parliament approved new ambitious targets for the transformation of the German energy system. A key strategy towards this transformation mandates a planned continuous increase in electricity from renewable energy sources: the fraction of total electricity supply from renewable energy sources shall increase to 80% in 2050 (35% in 2020; 50% in 2030; 65% in 2040, respectively).[1] Second it was decided to reduce Germany's primary energy demand to 80%, as compared to 2008 values, by 2020 and to 50% by 2050 [1]. In addition Germany supports the EU objective of reducing greenhouse gas emissions by 80–95% by 2050 compared to 1990 [2]. While the long-term targets are clearly defined, significant uncertainty still exists on which paths to take to achieve these targets as well as on what is the optimal mix on the generation, conversion and demand side. However, there is almost no doubt that energy savings on the demand side, energy efficiency in conversion chains and a large fraction of energy generated from renewable sources on the production side are the key elements for achieving these long-term goals.

In this paper we describe REMod-D (Renewable Energy Model-Deutschland), a newly developed model which performs a systematic optimization on two main sectors of the German energy system, namely the electricity sector and the heat sector, focusing on a future energy system characterized by a high renewable energy fraction. In a second paper we present and analyze results of the simulations carried out with the model described here [3]. Together the electricity and heat sectors cover about 53% of the final energy demand and are responsible for about 62% of the primary energy consumption (see Section 2). For the model development these two sectors were chosen for the following reasons:

– There is an increasingly strong link between the electricity sector and the heat sector: on the one hand an increasing number of electric heat pump systems are used for heating buildings and on the other hand an increasing number of combined heat and power systems (CHP) in a wide range of capacities is employed.
– Energy-saving building retrofit measures are considered to be a key element in increasing energy efficiency and as such it is included into the model.
– The sectors not covered by the model are fuel based energy consumption in the mobility sector (private cars, trucks, air transportation) and the industry. The long-term future of the fossil-fuel based mobility sector is uncertain under today's perspective. Various trends are visible and discussed. These include battery-powered cars, hydrogen-powered cars using fuel cell technology, trucks employing centralized electricity using trolley bus technology and many other concepts. A wide diversity exists today with regard to using fossil fuels in industrial processes. Many processes are available which have very different boundary conditions and varying potentials for efficiency measures at a variety of costs. Therefore, the mobility and industrial processing sectors remain more difficult to implement into a coherent energy-economic model based on hourly energy balance calculations as used in our model. As of now, they are left out of the model discussed here. However, their effect on the overall German energy balance is considered in Section 2 and briefly discussed again in the second part of this paper [3].

Various simulation models for national energy systems, which consider a high penetration of renewable energies, exist, but only a few models are able to combine the supply and demand from both the electricity and heat sectors. Many of the energy system models developed in the past focus on the electricity sector and its development but rather neglect the heat sector or do not cover it in detail. For example, the BALMOREL or the SIVAEL model cover the electricity sector but only district heating for the heating sector [4]. The EMCAS model focuses in detail on the operation of power systems [5]. A widely used example that covers both the electricity and the heat sector is the EnergyPLAN model developed in Denmark which has been applied to a number of different scenarios and regions [6–12]. The EnergyPLAN model calculates an optimal system configuration regarding heat production from solar thermal collectors, industrial CHP, decentralized and

[1] Bundesgesetzblatt No. 42, August 4th, 2011, Page 1634 http://www.bundesregierung.de/Content/DE/Artikel/2011/08/2011-08-05-gesetze-energiewende.html.

centralized CHP units, boilers, heat pumps and thermal storage. The electricity production is covered by photovoltaics, on- and offshore wind and conventional condensing power plants. Electricity storage is implemented by pumped hydro-power storage, batteries and the conversion of electricity into hydrogen. The optimization is based on hourly energy balances of supply and demand and is built to optimize technical regulatory strategies such as meeting heat demand or both heat and electricity demand [13]. Thus, the EnergyPLAN model helps to visualize the interaction and cost of heat and electricity producing and consuming technologies, but does not offer optimization of total system costs. A typical example for a model that focuses on the optimization of minimal energy system cost is the MARKAL model developed by the International Energy Agency (IEA) [14]. In contrast to the EnergyPLAN model, this model is used to optimize system cost and to represent the evolution of an energy system over a time period of several years. This model was used by the European Commission to determine the so called 20-20-20 targets [15]. Other models with a comparable aim are, for instance, IKARUS which performs optimizations for a time period of up to 40 years in time steps of 5 years [16] or PERSUS which focuses on the minimization of energy supply system relevant expenditures [17]. These cost optimization tools cover the heat sector to a certain extent, but there is no detailed description of the related influences like building retrofit or alternative future heating technologies for centralized and decentralized systems. To our knowledge, there is only one tool that focuses on the detailed description of the heating and building sector in the context of a complex energy system. This model, called Invert [18], determines the influence of policy schemes in the field of heating, domestic hot water and cooling through a detailed description of this sector. Nevertheless, there is no cost optimization for a one year time period with hourly time-steps and also the interaction with the electricity sector is not treated in detail. We developed the REMod-D model, introduced in this paper, to fill the gap between a detailed modeling of the building and electricity sector with our complex energy system involving both the electricity and the heat sector. Further, the total cost optimization of a complex future energy system with a high penetration of renewable energy sources is carried out in hourly time-steps over a simulation of one year.

2. Electricity and heat in Germany's national energy balance

In 2010 the total German primary energy demand amounted to 3629 TW h (this value and all of the values used in this section are based on those provided in [19] unless otherwise indicated). About 30% (1113 TW h) are attributed to losses and 70% (2516 TW h) are used to cover the final energy demand. In Table 2.1 the distribution of final energy between the different application sectors – industry, mobility sector, tertiary sector (commerce, trade and services) and private households – and among different areas of application is shown. The table also indicates which areas of application are covered or not in the REMod-D model. The main areas not covered in the model are non-electrically produced process heat in the industrial and tertiary sector and non-electrically produced mechanical energy in the mobility sector. In both of these areas, mainly fossil fuels are used today for either heating of industrial processes or in internal combustion engines for traction of private cars, trucks and non-electrically driven railed vehicles and for air transportation.

Summarizing for Germany in 2010, the overall heating demand for all buildings (private households, tertiary and industrial buildings) was 781 TW h, the hot water demand in all sectors was 105 TW h and the total electricity demand was 516 TW h. The electricity demand was higher in the years before the financial crisis. The corresponding values for the total electricity consumption were 539.6 TW h in 2006, 541.2 TW h in 2007 and 542.2 TW h in 2008 respectively [19]. Therefore we decided to base our calculations on an electricity demand of 500 TW h without electricity used for heating (39 TW h) and hot water (19 TW h). Heating and hot water are directly handled in the model and are therefore subtracted from the total electricity demand. The remaining electricity loads pertain to all applications except heating and hot water.

Table 2.1
Distribution of final energy consumption in Germany (2010) for different application sectors and different uses; values highlighted with bold face are covered in the REMod-D model.

2010 in TW h	Industry	Mobility	Tertiary	Private households	Total sectors
Heating	**54.4**	3.6	**187.9**	**534.9**	780.8
Thereof electricty	**0.9**	**0.8**	**10**	**27.1**	38.8
Hot water	**6.3**	**0**	**15.9**	**83.1**	105.3
Thereof electricty	**0**	**0**	**3.4**	**15.6**	19.1
Process heat	463	**0**	29.4	36.4	528.7
Thereof electricty	**37.5**	**0**	**7**	**35.7**	80.2
Comfort cooling	**4.6**	0.7	2.8	0	8.1
Thereof electricty	**4.6**	**0**	**2.2**	**0**	6.9
Industrial refrigeration	**4.9**	**0**	9.1	**25.8**	39.8
Thereof electricty	4.9	0	9	**25.8**	39.7
Mechanical energy	153.5	699.5	59.9	**3.1**	916
Thereof electricty	**150.7**	**14**	**30.5**	**3.1**	198.3
Information technology	**8.8**	2.9	**21.2**	**22.3**	55.2
Thereof electricty	**8.8**	**0.8**	**21.2**	**22.3**	53.1
Artificial lighting	**10.4**	3.5	**56.9**	**11.3**	82.1
Thereof electricty	**10.4**	**0.8**	**56.9**	**11.3**	79.4
Total uses	705.9	710.2	382.9	716.9	2516
Thereof electricty	217.9	16.5	140.1	141	515.5

3. Modeling approach

The basic concept of the REMod-D model is to set up a fixed topology of energy producers, converters, storage devices and consumers and to optimize their sizing to meet the goal of minimized annual overall cost. The optimization rescinds – at least in this first step – completely from the existing infrastructure of the German energy system, i.e., the approach can be characterized as a “Green Field” simulation.

As a first case, a system has been defined which covers the demand in the electricity and heat sector completely by renewable energies harvested in Germany and in which no energy exchange with neighbor countries is allowed (further called “100% scenario”). A schematic of the implemented complete system is shown in Fig. 3.1. This system contains photovoltaic power systems, on- and offshore wind generators and hydro power stations as primary electricity generators. Solar thermal collectors, connected either to central heating systems or to decentralized heating systems, act as primary heat generators. The secondary electricity generators are combined heat and power systems (centralized, decentralized) and combined cycle power plants. Both use either gas from biomass or gas produced from primary renewable electricity (power-to-gas). The electric load is given by the total load of all electricity consumers connected to the public grid which are not used for heating and hot water plus the electricity loads that are due to electrically driven heat pumps. Heat loads are separately treated for buildings which are connected to a centralized heat production (district heating networks)

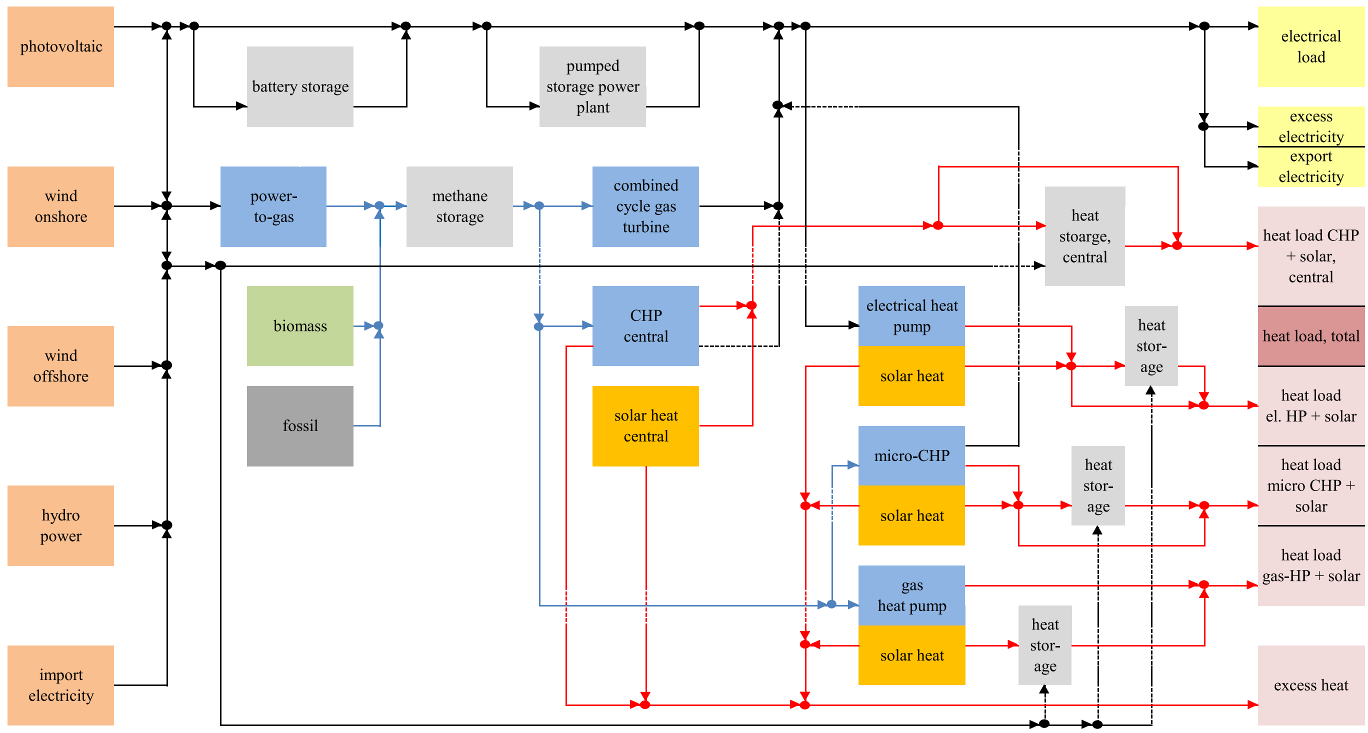

Fig. 3.1. Topology of the model of the German energy system (electricity and heat sector) of the REMod-D model.

and buildings which have a decentralized heating system. For buildings having a decentralized heating system, three technologies are distinguished, namely electrically driven heat pumps, decentralized combined heat and power systems and gas driven heat pumps. The latter is considered as the follow-up technology of the gas and oil boilers (condensing, non-condensing) predominantly used today in Germany. Five different types of storage are included in the model: pumped hydro-power storage and batteries for the direct storage of electricity, gas storage (in Germany typically large caverns) for storage of gas from renewables (power-to-gas) as well as centralized and decentralized heat storage.

Today two main technologies are being discussed for the conversion of renewable electricity into synthetic fuel for long-term storage: (1) The production of hydrogen and its use in various applications and (2) the conversion of the produced hydrogen into methane (Sabatier-process) for use in the existing natural gas infrastructure (pipes, storage devices). While the second path has the disadvantage of lower overall efficiency and higher converter costs due to the additional conversion step, it has the advantage of being fully compatible with the existing natural gas infrastructure. For our model we therefore chose to investigate the case of methane production from renewable energies since the cost for all of the involved components that are necessary to maintain a natural gas grid are more transparent. In future models we aim to integrate the cost of the hydrogen infrastructure and to compare the two options.

A single simulation is carried out as follows:

- Capacity values are defined for all generation, conversion and storage components of the energy system.
- An hour-by-hour simulation is carried out for a typical year. A complete energy balance is computed for each hour of the year following the operation scheme described in Section 5.
- This annual simulation is repeated with modified values of the capacity of photovoltaic until the annual energy balance is fulfilled, i.e., until long term storage devices (centralized heat storage, gas storage) have the same storage content at the beginning and end of the year.
- The total annual cost of this system is calculated. This cost is only composed of re-investment in order to replace components at the end of their lifetime and operation and maintenance (O&M) cost. No cost for fossil fuels or uranium for nuclear plants arises since the system is operated by 100% renewable energy sources (for more details see Section 6).

Many simulation runs are performed for different parameter sets, i.e., different compositions of the capacities of all components. A systematic parameter modification is carried out in order to identify the system composition which leads to minimized overall annual cost. A fast convergence algorithm has been developed and implemented for parameter modification in order to achieve a small computer run time and to carry-out sensitivity studies in affordable time (for more details see Section 6).

Beside the “100% scenario”, two further scenarios were considered: a scenario in which import of electricity is permitted and a scenario which allows the use of some fossil fuel. In these scenarios the general approach of simulation and optimization is not changed. However, in the import scenario a maximum capacity of import of electricity has been fixed and the result on the sizing of the system components has been studied. In the fossil fuel scenario a pre-defined amount of fossil fuels is used and all components are optimized under this modified boundary condition.

4. Models of single components

In the following, the models used and cost figures for all components as well as all assumptions made are described. Cost figures are based on expected future costs based on learning curve models. This means that for all technologies a future cost value is assessed which is expected to be achieved after broad market

introduction and exploitation of cost saving potentials by large scale production and main steps of technology advancement. Today different technologies have, of course, achieved different levels of development and thus the distance to the assumed future cost value is different. We investigated the important literature on each technology and in case of different statements regarding expected future cost, we used average values in our model.

4.1. Load components

4.1.1. Electric load

The annual German electricity demand used in the calculations amounts to 500 TW h without electricity used for heating and hot water. The electricity for heating and hot water is determined by the simulation (see Section 4.3 on electrically driven heat pumps). This value is assumed to remain constant, i.e., no cost related efficiency measures have been implemented in the model and thus they have not been subject of optimization. To distribute the electricity demand over 8760 h in a year, we used the hourly load profile of 2011 published by the European Network of Transmission System Operators for Electricity (ENTSOE). Such load data is referred to as the hourly average active power absorbed by all installations connected to the transmission network or to the distribution network. As it is calculated as an average value for every hour, it is not entirely precise but of sufficient quality for the purpose of this model [20].

4.1.2. Heating load

The annual heating energy for the entire German building stock amounts to 780.8 TW h (2010) [19]. This heating demand corresponds to the total amount of all buildings in the residential, tertiary and industrial sector. All these buildings together represent a heated useful floor area of 6300×10^6 m² (3400×10^6 m² residential [21], 2.300×10^6 m² [22] and ca. 600×10^6 m² based on own calculations[2]). The hourly heating demand, P_{heating}, is calculated in a simple way by the following equation:

$$P_{\text{heating}} = \begin{cases} 0 & \text{if } T_{\text{amb}} > T_{\text{set}} \\ k(T_{\text{set}} - T_{\text{amb}}) & \text{if } T_{\text{amb}} \le T_{\text{set}} \end{cases} \tag{1}$$

T_{amb} denotes the ambient air temperature (dry bulb temperature) of the particular hour and T_{set} a set temperature for operation of heating systems. In the simulation T_{set} was set as 15 °C. k is a constant factor chosen such that the overall sum equalizes the total annual value. The resulting annual profile of daily heating energy sums is displayed in Fig. 4.1.

In the German energy policy energy-saving building retrofit is seen as one of the key measures for reducing the consumption of fossil fuels and related CO_2 emissions (see e.g. [1]). In order to include energy-saving building retrofit into the optimization process of the REMod-D model, an average cost curve for retrofit measures has been developed. A number of studies on the cost of energy-saving building retrofit in Germany indicate that the specific cost, i.e. investment per unit of saved energy, increase disproportionate with an increase in the achieved level of energy standard [23–26]. Fig. 4.2 shows the cost curve which was approximated based on numbers from [23,25]. It is important to note that the cost covered by this function represents only the extra value for energy-saving retrofit measures. Basic building retrofit to keep a building operational without reducing its energy demand is not covered in this cost value. For the purpose of our model is assumed that this extra cost is also needed in future building retrofit after the life cycle of energy saving measures has been achieved.

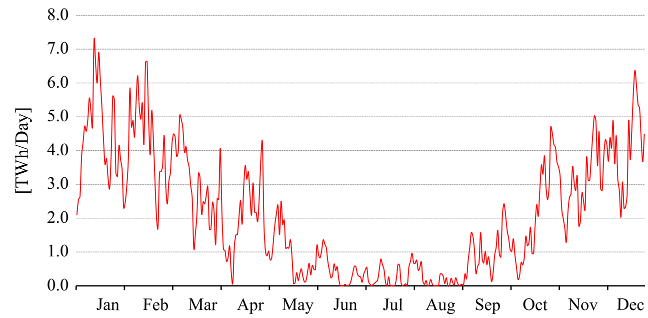

Fig. 4.1. Annual time pattern of daily low temperature heating demand.

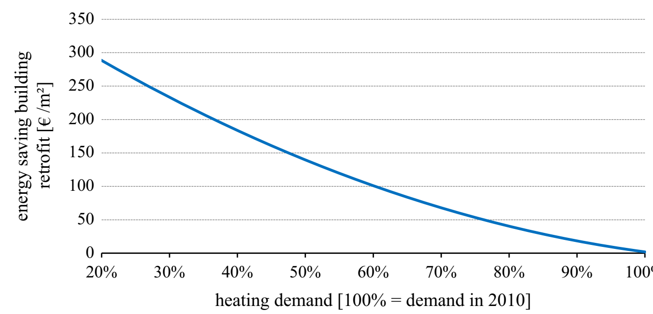

Fig. 4.2. Average investment cost for energy-saving building retrofit per unit of floor area in Germany as used in the simulation. The x-axis denotes the level of heating energy demand per floor area in a percentage of the average value of 2010 (average value 124 kW h/(m²a) for all buildings).

Table 4.1
Summary of used values for electricity, heating and hot water load.

Load type	Annual demand (2010) in TW h	Cost information	Subject of optimization	Data sources, references
Electricity	500	n.a.	No	[19,20]
Heating	780.8	See Fig. 4.1	Yes	[19,21–23,25]
Hot water	105.3	n.a.	No	[19]

4.1.3. Hot water load

The annual energy demand for hot water in the total German energy sector amounts to 105.3 TW h (2010) [19]. This hot water demand corresponds to the total amount of all buildings in the residential, tertiary and industrial sector. For simplicity reasons this value was equally distributed over all hours of the year, i.e., the amount in each single hour is 12,015 MW h. It is assumed that this value remains constant, i.e., no cost related efficiency measures have been implemented in the model.

Key values on load components are summarized in Table 4.1.

4.2. Generation components

4.2.1. Offshore wind

To simulate the electricity generation by offshore wind power plants, a feed-in curve is used which represents the quarter-hourly feed-in of all German offshore plants in the North Sea connected to the transmission grid of TSO TenneT in 2011 [27]. This feed-in curve has been transformed by building the weighted arithmetic mean of every quarter of an hour and normalizing all values on the average installed capacity. The resulting curve represents roughly 3500 full load hours. Used economical values are 1650 €

[2] This value is estimated based on the total amount of heat for space heating in the industrial sector (ca. 54 TW h, cf. Table 2.1) assuming that the structure is similar to the structure in the tertiary sector.

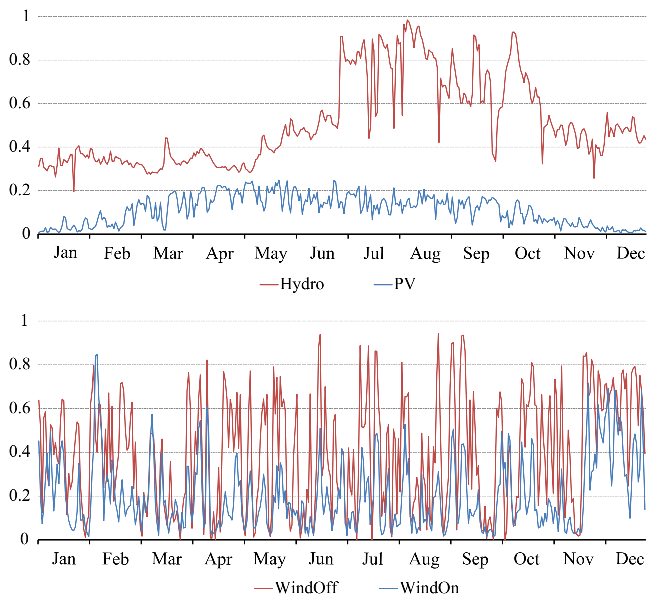

Fig. 4.3. Electricity generation profiles used in the simulation (daily averages of hourly electricity production for the four renewable energy technologies per GW of installed capacity). Top: PV and hydro; bottom: offshore wind and onshore wind.

investment per kW of installed capacity and a lifetime of 25 years [28–30][3] [31]. The annual profile (daily averages) of electricity generation by offshore wind per GW of installed capacity used in the simulation is shown in Fig. 4.3. The used values are summarized in Table 4.2.

4.2.2. Onshore wind

For the electricity generation of wind onshore in Germany in 2011, the same method as described above is used, applying a different source [32]. The feed-in curve has been transformed by normalizing all values on the average installed capacity of the corresponding month, since continuous installation and re-powering takes place. The used values (annual full load hours, specific investment cost and lifetime) are summarized in Table 4.2.The annual profile (daily averages) of electricity generation by onshore wind per GW of installed capacity used in the simulation is shown in Fig. 4.3.

4.2.3. Photovoltaic systems

For the electricity generation and the transformation of the feed-in curve of photovoltaic in Germany in 2011 the same method as described above is used, applying a different source [33]. The used values (annual full load hours, specific investment cost and lifetime) are summarized in Table 4.2. The annual profile (daily averages) of electricity generation by photovoltaic systems per GW of installed capacity used in the simulation is shown in Fig. 4.3.

4.2.4. Hydropower

To simulate electricity generation by hydropower stations, a feed-in curve representing the hourly feed-in of a share of installed hydro power stations in Germany in 2011 is used as a basis [34]. Due to its incompleteness, the values of this feed-in are normalized and then scaled up on the installed capacity. The used values (annual full load hours, specific investment and lifetime) are summarized in Table 4.2. The annual profile (daily averages) of electricity generation by hydropower stations per GW of installed capacity used in the simulation is shown in Fig. 4.3.

Annual profiles of the electricity production (daily sums) of the four renewable energy production technologies are shown in Fig. 4.3.

Values used for the modeling of electricity generation components are summarized in Table 4.2.

4.2.5. Solar thermal collectors

Solar thermal collector systems enable a direct conversion of solar energy into heat. These systems may be connected to district heating networks or installed in decentralized installations in single buildings. Such systems can cover part of the hot water load and part of the space heating load. However, due to the seasonal mismatch between the space heating load and solar gains, the contribution to the heating is relatively small unless seasonal storage is used (see Section 4.4). For solar collectors the hourly useful collector energy output, $Q_{use,i}$, is calculated for each hour based on the actual hourly average global radiation on the solar collector, G_i, and the difference between the actual storage temperature, T_{stor}, and the actual hourly average ambient air temperature, T_{amb}, by the following collector equations:

$$Q_{use,i} = A_i \times G_i \times \eta_{coll,i} \times 3600 \text{ s} \quad \text{with}$$

$$\eta_{coll,i} = \left[c_0 - c_1 \times \left(\frac{T_{Stor} - T_{amb,i}}{G_i} \right) \right]^+ \tag{2}$$

$\eta_{coll,i}$ denotes the collector efficiency and c_0 and c_1 are the optical efficiency and the heat loss coefficient of the collector, respectively. The + on the squared bracket indicates that the expression is only used if the result is greater than zero and is otherwise set to zero. The index i represent three different orientations (south-east, south, south-west) and two different sites which represent southern Germany (Würzburg) and northern Germany (Braunschweig). The total collector area, A_{tot}, was divided into six different sub-areas and for each area the actual global radiation on the tilted collector (45° slope) was computed for each hour using the software DESIRE [36]. Using the ambient air temperature of each location, the collector equations were solved and the total useful collector output for each hour, $Q_{use,tot}$, was calculated by summing the six single values for each sub-area,

$$Q_{use,tot} = \sum_{i=1}^{6} Q_{use,i}. \tag{3}$$

It was assumed that 50% of the total collector area is located in the south and 50% is located in the north of Germany. And it was assumed that 30% of the total collector area is oriented south-east, 40% is oriented south and 30% is oriented south-west. This approach was applied in order to take spatial and angular distributions of solar thermal collector systems into consideration.

The values for optical efficiency, c_0, and heat loss coefficient, c_1, as well as cost values used in the simulations are summarized in Table 4.3.

4.3. Conversion components

Following the topology chart in Fig. 3.1, there are five energy converters in the modeled energy system. These converters are described below and imply the conversion of power-to-gas, gas-to-power, gas-to-power-and-heat, power-to-heat, and gas-to-heat. Table 4.4 summarizes all performance and cost values used for conversion components.

4.3.1. Power-to-gas

The production of synthetic gas (such as hydrogen or methane) is one of the options to generate chemical fuels from renewable

[3] All values from [29] are given in USD and are converted into € with an exchange rate of 1.3 USD/€.

Table 4.2
Summary of used values for electricity generation components.

Generation technology	Full load hours p.a.	Specific cost in € per kW	Lifetime in years	O&M cost in % of investment	Subject of optimization	Data sources, references
Offshore wind	3500	1650	25	3.0	Yes	[27,30]
Onshore wind	1800	1150	25	2.0	Yes	[30,32]
Photovoltaic	975	950[a]	25	1.0	Yes	[30,33]
Hydro-power	4500	2400	50	2.0	No (fix value 4,7 GW)	[28,29,34,35]

[a] This number is calculated assuming that 75% of the photovoltaic facilities are installed on rooftops and 25% in utility scale on other areas.

Table 4.3
Summary of used values for solar thermal collectors.

Solar thermal collectors	Efficiency values	Specific cost in € per m²	Lifetime in years	O&M cost in % of investment	Subject of optimization	Data sources, references
Large fields	Optical efficiency c_0: 0.8	140[a]	20	1.4	Yes	[28,29]
Decentralized systems	Heat loss coefficient c_1: 3.0 W/(m² K)	270[a]	20	1.3	Yes	[29,38]

[a] The value gathered from [29] is given per kW. To calculate the costs in €/m² a conversion factor of 0.7 kW/m² from [37] is used.

Table 4.4
Performance and cost values of conversion technologies used in the REMod-D model.

Conversion technology	Conversion efficiency, COP		Lifet-ime in a	O&M cost in % of invest-ment	Specific cost		Subject of optimi-zation	Data sources, references
	Value	Unit			Value	Unit		
Power-to-Gas	0.6	kW_{Gas}/kW_{el}	17	3.0	1500	€/kW_{el}	Yes	[40]
Combined cycle	0.65	kW_{el}/kW_{Gas}	30	3.0	640	€/kW_{el}	Yes[a]	[41–43]
CHP, centralized	0.65[b]	kW_{el}/kW_{Gas}	24	3.0	650[c]	€/kW_{el}	Yes	[29,49,50]
	0.55[d]	kW_{el}/kW_{Gas}						
	0.35[d]	kW_{th}/kW_{Gas}						
CHP, decentralized	0.33	kW_{el}/kW_{Gas}	25	3.0	1400[c]	€/kW_{el}	Yes	[29,50]
	0.52	kW_{th}/kW_{Gas}						
Electric heat pump	See Fig. 4.4	kW_{th}/kW_{el}	20	1.5	1050	€/kW_{th}	Yes	[28,51]
Gas heat pump	See Fig. 4.4	kW_{th}/kW_{Gas}	20	1.5	800	€/kW_{th}	Yes	Own assumptions
Condensing boiler, centralized	0.98	kW_{th}/kW_{Gas}	20	1.0	90	€/kW_{th}	No	[52,53]
Condensing boiler, decentralized	0.96	kW_{th}/kW_{Gas}	20	1.0	670	€/kW_{th}	No	[52,54]

[a] The capacity of the combined cycle is determined in such way that in the worst-case hour the required electricity demand is satisfied.
[b] Values used for electricity only production, no heat use. Today's highest value is 62% [49] and we assume a further increase until 2050.
[c] These values are calculated with today's cost from [50] and are reduced with a cost degression factor of 0.6 and 0.75 for decentralized small scale and centralized large scale CHPs, respectively, according to the numbers from [29].
[d] Combined mode: Electricity production and heat use.

electricity. Additionally for methane it opens the possibility to use distribution and storage systems that are available already today. In particular in Germany, a lively discussion is ongoing about the production of synthetic fuels as an option to overcome seasonal mismatches between renewable energy availability and loads. Also the pros and cons of using hydrogen directly or its further conversion into methane is actively discussed [39]. In our model we implemented a general power-to-gas component in a very simple way by assuming a constant conversion efficiency of 0.60 from power to gas. This is the average conversion value for electricity into methane, which is highly dependent on the CO_2 source that is needed for the methane production [40]. The potential long-term future cost of this technology has a broad range of values. Therefore, we took an average value of 1500 € per $kW_{electric}$ at a lifetime of 20 years [40].

4.3.2. Combined cycle power plants (gas-to-power)

Combined cycle power plants are large scale high-efficiency units for the conversion of gas (natural gas or synthetic gas from renewables) into electricity. Since they are installed with large capacity, it is often difficult to make use of the waste heat. Also, the amount of waste heat is comparatively small due to the high conversion efficiency for electricity production. We used the following values: conversion efficiency of 0.65 and long-term cost of 640 € per $kW_{electric}$ at a lifetime of 30 years [41–43].

4.3.3. Combined heat and power plants (gas-to-power-and-heat)

Combined heat and power plants (CHP) are used for a simultaneous production of electricity and heat from gas (natural gas or synthetic gas from renewables). In our model we considered two different types of CHP sizes, namely large units which are operated in combination with district heating networks and small units which are installed in a single building. For large systems we assumed that they can be either operated in combined mode where they produce electricity and heat or in a mode where only electricity is produced. The first operation mode has a lower electric performance and is only employed if heat can be used either by directly feeding the heat load or charging centralized heat storage. Large and small systems differ by both conversion efficiency and cost. All values used in our model are summarized in Table 4.4. Conversion efficiency values for heat, η_{Heat}, and

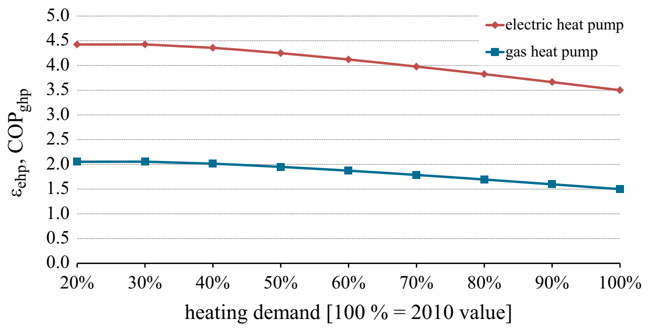

Fig. 4.4. Dependence of heat pump performance (ε_{ehp} for electric heat pumps, COP_{ghp} for gas heat pumps) from building energy standard, expressed as heating demand in a percentage of the 2010-value.

electricity, $\eta_{Electricity}$, are defined as:

$$\eta_{Heat} = \frac{Q}{E_{Gas}} \quad \text{and} \quad \eta_{Electricity} = \frac{E_{electric}}{E_{Gas}} \tag{4}$$

with E_{Gas} denoting the energy content of the gas and Q and $E_{electric}$ representing the useful heat output or electric energy output, respectively.

4.3.4. Electrically driven heat pumps (power-to-heat)

Electrically driven heat pump systems can be used for space heating application as well as for production of hot water. For this purpose they may use different heat sources such as the ground, ground water or ambient air. These systems enable a much more efficient conversion of electricity into heat compared to simple heaters based on electrical resistances. Therefore, in our model, only heat pumps for the conversion of electricity into heat were considered as electrically operated heating systems. However, heat rods can be utilized for converting surplus electricity to heat (cf. Fig. 5.3). Based on long-term monitoring of many heat pump systems throughout Germany, detailed figures about their long-term performance exist [44,45]. Based on these results, we assumed a conversion factor of electricity into heat, ε_{ehp}, defined as

$$\varepsilon_{ehp} = \frac{Q}{E_{electric}} \tag{5}$$

We assumed that this factor depends on the energy standard of the building sector. This is based on the fact that low temperature heating systems can be employed in buildings with a lower heating demand. The lower the supply temperature of the heating system, the higher is the energy performance of the heat pump. The used function is shown in Fig. 4.3; it takes into consideration that with decreasing heating demand for buildings the relative share of hot water demand increases. The hot water production always requires a temperature of about 60 °C and is not dependent on the energy standard of the building. Further values used in our model (cost, lifetime) are summarized in Table 4.4.

4.3.5. Gas-driven heat pumps (gas-to-heat)

The dominating technologies used today to convert fossil fuels into heat are oil or gas boilers. At a maximum, these systems convert the energy in the fuel into the same amount of low temperature heat. An increasing number of systems installed in the heating markets are condensing boilers which also make use of the condensing heat of water vapor in the exhaust gas of the burner. Recently, a number of developments focus on the substitution of this heating technology by more efficient systems, i.e. systems which better exploit the exergy content of the fuel. First field test results indicate coefficient of performance values, COP_{ghp},

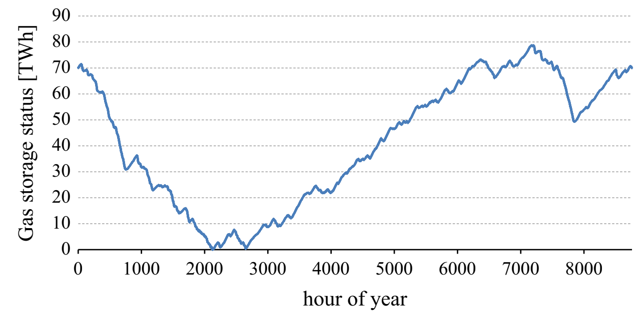

Fig. 4.5. Example of the annual time pattern of gas storage filling status.

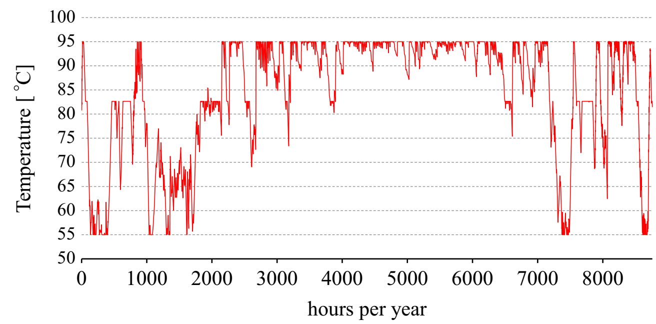

Fig. 4.6. Example of the annual time pattern of the temperature of centralized heat storage devices (water).

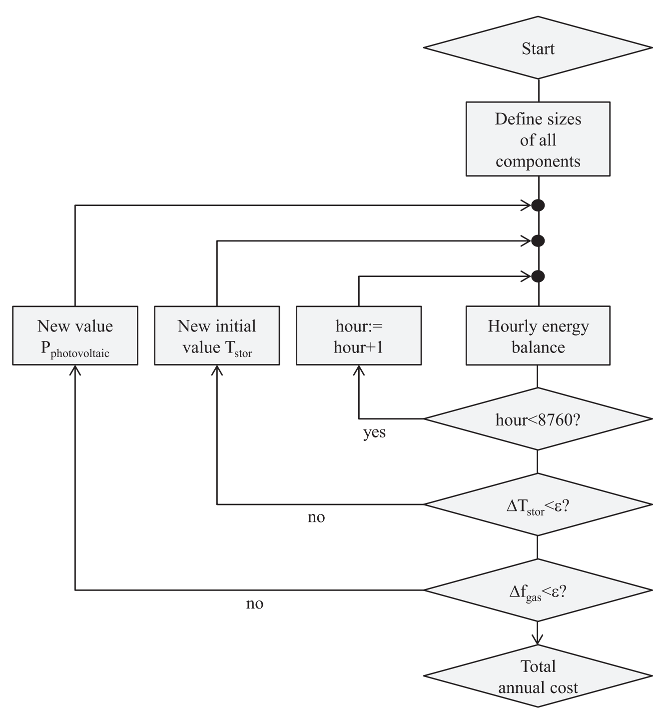

Fig. 5.1. Flowchart for a single simulation with fixed values of all components (except capacity of photovoltaic which is adjusted in order to fulfill the condition of a neutral energy balance). ΔT_{stor} denotes the absolute value of the difference between the storage temperature of the previous and the recent iteration step. Δf_{gas} denotes the absolute value of the difference of the filling status of the gas storage of the previous and the recent iteration step.

defined as

$$COP_{ghp} = \frac{Q}{E_{Gas}} \tag{6}$$

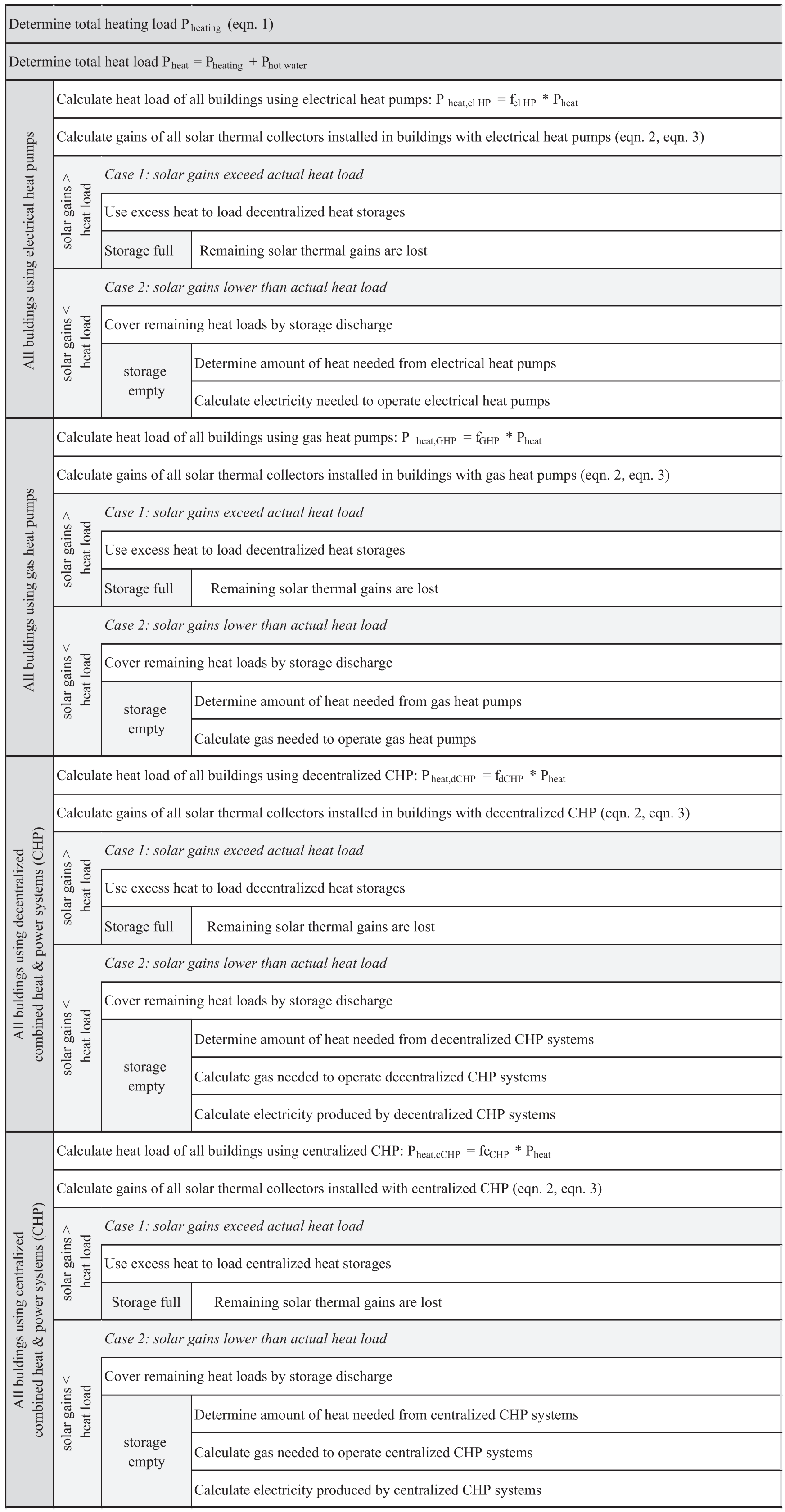

Fig. 5.2. Approach (operation cascade) for treating heat sub-systems (solar gains = hourly output of the corresponding solar thermal collector).

of up to 1.4 ([46–48]. As this technology is still in its early infancy, a significant increase in performance can be expected and we assumed that COP_{ghp}-values as shown in Fig. 4.4 will be reached in the future. The values still lie significantly below the theoretical limit defined by two combined Carnot-cycles operating in opposite directions and exploiting the high temperature of the exhaust gas

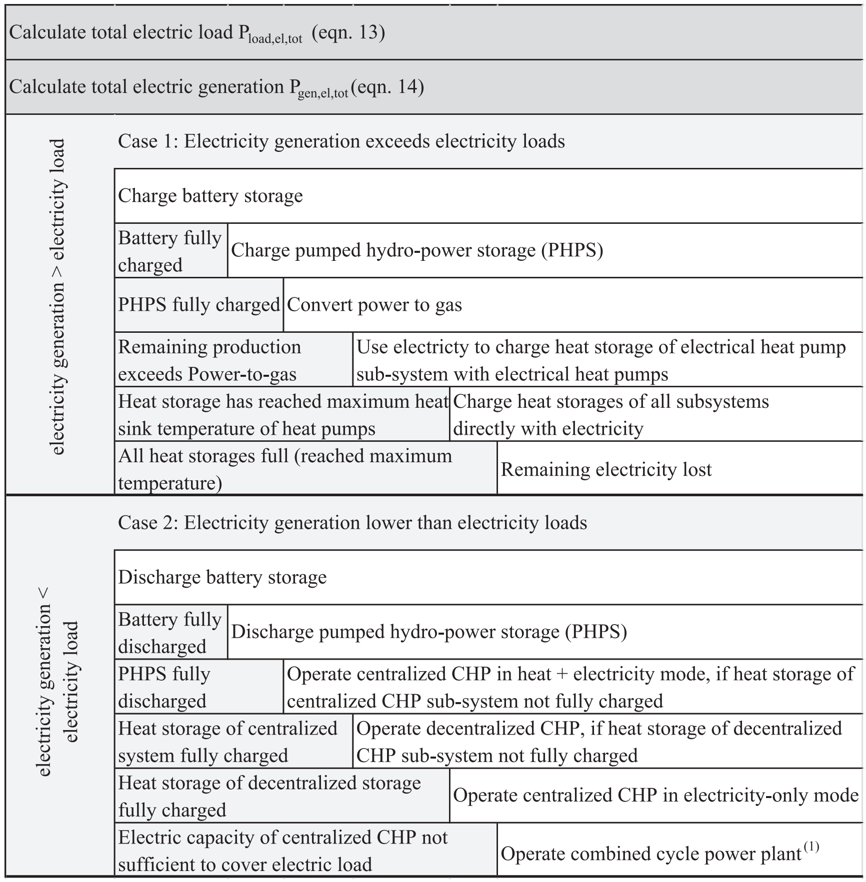

Fig. 5.3. Approach (operation cascade) for treating the electricity sub-system for the "100% scenario" (1) the capacity of the combined cycle is sized such that in each hour, i.e. also in the worst-case hour, the required electricity demand is satisfied.

of the gas flame. All values used in our model are summarized in Table 4.4.

Table 4.4 summarizes all performance and cost related values of the conversion technologies described above and used in the REMod-D model. It should be noted that the cost for all heating technologies will be reduced later in the calculation with the cost of a standard centralized or decentralized heating technology, namely a condensing boiler using gas for district heat or for on-site heating, respectively. Since these technologies would have to be installed anyway, the basic cost of standard reference technologies is not considered. However, we assume that in a future energy system using predominantly renewable energies, only technologies which enable a reasonable thermodynamic efficiency will be justified. The given costs include the cost for the heat source and its exploitation.

4.4. Storage components

Storage components will play a central role in a future energy system with a high share of non-dispatchable renewable energy sources. Three principle types of storage are contained in the REMod-D model: electricity storage (pumped hydro-power storage, batteries), gas storage (caverns) and heat storage (centralized, decentralized).

4.4.1. Pumped hydro-power storage

The total installed storage capacity of pumped hydro-power storage in Germany is about 40 GW h with a maximum total power capacity of about 6.7 GW [55]. A number of expansions of existing installations or new storage systems are under development or in the planning phase. We assumed that a total storage capacity of 60 GW h at a power capacity of 10 GW will be available in future. This number is not a subject of optimization and has been set as a constant in all simulation runs. The overall storage conversion efficiency is assumed as 0.8 [56]. All values including lifetime and cost values are summarized in Table 4.5.

4.4.2. Batteries

Batteries store electricity in an electro-chemical process with high efficiency. Both the need for storage of non-dispatchable renewable electric energy as well as the interest in electro-mobility concepts for private cars stimulated a lot of R&D activities worldwide and lead to a strong technology improvement in this sector. A number of studies discusses potential future cost and performance of battery systems [42,57]. In the REMod-D model we used a very simple battery model which describes the performance by a simple single value for the overall storage efficiency. Used values including lifetime and cost values are summarized in Table 4.5.

4.4.3. Gas storage

Germany's capacity for the storage of natural gas is in the range of 35 billion m³, which corresponds to about 350 TW h. In our model we assumed that this storage capacity is available for storage of synthetic gas produced by renewable electricity in power-to-gas converters. During simulation we only controlled that the needed gas storage capacity which results from optimization does not exceed this limit. Furthermore we assumed that 1% of the energy is lost or used for operation [58] of the gas network and that there is no extra investment due to the already existing

Table 4.5
Performance and cost values of storage systems used in the REMod-D model (PHPS: pumped hydro-power storage)

Storage type	Energy performance			Cost parameters				Subject of optimization	Data sources, references
	Performance parameter	Value	Unit	Specific cost	Unit	Lifetime in a	O&M cost in % of invest-ment		
PHPS	Overall efficiency (out/in)	0.8	kW h_{el}/kW h_{el}	1600	€/kWel	60	1	No	[29,56]
Battery		0.9	kW h_{el}/kW h_{el}	300	€/kW h_{el}	15[a]	1	Yes	[42,57]
Gas		0.99	kW h_{Gas}/kW h_{Gas}	–	–	–	–	No	[58]
Heat (water), centralized	Charge efficiency	0.75	kW h_{th}/kW h_{th}	20	€/m³	40	1	Yes	[59]
	Time constant	180	Days						
	Min. temperature	55	°C						
	Max. temperature	95	°C						
Heat (water), decentralized	Charge efficiency	0.9	kW h_{th}/kW h_{th}	Cost contained in system cost for heating system		20	1	No	[52]
	Time constant	72	h						
	Min. temperature	55	°C						
	Max. temperature	95	°C						

[a] This is equivalent to around 3000 load cycles, assuming that the battery is used 200 days per year.

infrastructure. Fig. 4.5 shows an example of the annual filling status of the gas storage for one of our simulations. The maximum capacity of approximately 80 TW h lies significantly below the maximum capacity. The main discharging time is in winter and the main charging time in summer. The filling status at the end of the year is equal to the filling status at the beginning of the year, which confirms that the annual energy balance is fulfilled.

4.4.4. Centralized heat storage

Centralized heat storage using water as storage medium is an interesting option for long-term storage which can help to overcome long-term (up to seasonal) mismatches in the heating sector. For instance in Denmark many very large heat storage installations have been realized in the past years and many more are recently in the planning or construction phase, respectively [59]. All these storage devices are connected to district heating networks and in many installations large solar thermal collector fields have been installed in addition to other heat supply systems such as heat pumps or combined heat and power plants.

The physical model used in the REMod-D simulations is a simple single-node model. As such, it underestimates the positive impact of stratification which is particularly beneficial for the performance of solar thermal collectors. The energy balance of the heat storage is given by the following differential equation:

$$C_{Stor}\frac{dT_{Stor}}{dt} = \eta_{charge} \times P_{charge} - P_{discharge} - P_{loss} \quad (7)$$

with

$$P_{loss} = UA_{Stor}(T_{Stor} - T_{amb,Stor}) = \frac{C_{Stor}}{\tau_{Stor}} \times (T_{Stor} - T_{amb,Stor}) \quad (8)$$

In above equations C_{Stor} denotes the total heat capacity of the storage, T_{Stor} the storage temperature, η_{charge} the efficiency during storage charge (accounting for pipe losses), P_{charge} the total heat power supplied to the storage, $P_{discharge}$ the total heat power that is removed from the storage, P_{loss} the storage losses, UA_{Stor} the total heat loss coefficient, $T_{amb,Stor}$ the storage ambient temperature (ground temperature in case of a water store in the underground) and τ_{Stor} the time constant of the storage for self-discharge. This differential equation has been solved numerically using the Euler method.

Fig. 4.6 shows the example of the annual time pattern of the temperature of centralized heat storage (water storage). The storage is mainly employed as long-term storage. All used values including lifetime and cost are summarized in Table 4.5.

4.4.5. Decentralized heat storage

Decentralized heat storage devices have two main functions in the energy system of buildings: on the one hand they can overcome mismatches between solar thermal energy supply and heat loads and on the other hand they can absorb excess renewable electricity either indirectly through heat pumps or directly by converting electricity into heat. The last option should, of course, only be used if another thermodynamically more favorable use is not possible (see Section 6).

In our model we assumed that 800 l of hot water buffer storage per 10 kW of heating capacity are installed for decentralized heating systems which interact with the electricity grid (e.g. electrical heat pump, decentralized combined heat and power system). In the case of gas heat pumps, the storage size is not linked to the capacity of the heat pump but to the size of a solar thermal collector which may be installed in addition to the gas heat pump. Here we assume that 80 l of buffer storage are installed per m² of collector area. Thus, the capacity of decentralized heat storage is not a subject of optimization but is strictly linked to the capacity of the above mentioned decentralized heating systems (which all are subjects of optimization).

The physical model applied for decentralized heat storage is similar to the one applied for centralized heat storage and is described above. Values of the parameters used for decentralized heat storage are summarized in Table 4.5.

4.5. Other aspects regarding the German energy system

Other components of the overall energy system are the grids (electricity, gas, heat) and other resources such as biomass and fossil fuels in cases of less than 100% renewable energy. The import and export of electricity has a part in a European transnational electricity grid and is an option for energy management.

4.5.1. Electric grids

The existing German electricity network has a total length of 1.78 Mio kilometers of which 1.16 Mio km belong to the low voltage level, about 507,210 km to the medium voltage level, 76,279 km the high voltage level and about 35,708 km to the

ultra-high voltage level [60]. While more than 70% of the low and medium voltage levels are installed underground, the majority of the high and ultra-high voltage levels are installed as overhead lines.

To consider the cost for the needed expansion of the electricity grid infrastructure, we calculate average costs to simplify the large variety of data. The low voltage grid is mainly influenced by the expansion of photovoltaic capacity. To calculate the expenses of a grid expansion due to an increase in photovoltaic electricity, we multiply the installed capacity with an average value of 140 €/kW_{el} and consider a lifetime of 40 years according to data from [61]. The cost to cover the increased grid capacity due to the expansion of offshore windmills in the North Sea and the Baltic Sea is considered in two steps. First, an average cost of 430 € [62] per kW_{el} installed capacity of offshore wind power at an average length of 20 km and a lifetime of 40 years [63] is implemented to consider the interconnection lines that are needed to connect the windmills to the land-based grid. Second, due to a higher electricity demand in southern Germany, we assume that 40% of the electricity produced in the North Sea must be transported through high voltage lines to the south. Accordingly, the grid capacity of these high voltage lines is sized to deliver this 40% share of the installed offshore wind capacity. The cost is assumed with 200 €/kW_{el} [64] at an average length of 400 km and a lifetime of 80 years [64].

In 2008 the internal consumption of the electricity production sector in Germany, including losses and electricity for pumps in power plants, amounted to 72.4 TW h at a total production (including import) of 677.3 TW h [19]. This corresponds to an efficiency of 89%. Since the majority of the electricity consumption in the systems considered here is provided by wind converters and photovoltaic systems, the net electricity production of each power generator is higher because the need for internal pumps, which are necessary for the operation of conventional power plants, will be much lower. Also a more decentralized production with a higher spatial coincidence of production and consumption will lead to shorter distribution distances and thus to reduced losses. Therefore we assumed an overall efficiency of 95% for the electricity grid.

4.5.2. Gas networks

The total length of the existing German natural gas network is about 443,000 km. It operates at three different pressure levels. In our model we did not calculate any cost related to the O&M of the gas network. We assume that the impact of the sizing of gas related components is very small with respect to the overall cost of O&M of the gas network.

4.5.3. Heat networks, district heating networks

District heating networks enable a common operation of various heat producers and consumers that are connected through a network which is operated by either water or steam as heat transfer fluid. Here the integration of large heat storage devices is possible, which assists in overcoming mismatches between heat production and heat consumption.

The major cost of district heating networks is due to the connections to the building and the heat transfer units in the building, while the far-reaching central network contributes less to the overall cost. In our analysis we calculated the overall cost of district heating networks as a function of the total maximum heating capacity (including heating of hot water) covered by centralized heat supply. This value is multiplied with a specific average cost value of 400 € per kW [65].

4.5.4. Biomass

The total amount of biomass used in Germany for energy applications amounted to 311 TW h in 2010 [19]. About 50% of this corresponds to solid biomass (e.g. wood, wood chips), 18% to liquids (e.g. biodiesel) and 32% to gaseous biomass (e.g. biogas, waste gas). From today's perspective, it is very uncertain how much biomass will be available for energy purposes in the future. Since almost all biomass products can be transformed into high temperature heat, we assume that a major part of future biomass used for energy purposes is used for industrial process heat generation and – in particular in its liquid or gaseous form – for the mobility sector. Due to this uncertainty we assumed that 50 TW h are available for the electricity and heat sector and that it is only used in combination with conversion processes with a high thermodynamic efficiency, i.e., not for direct production of low temperature heat for space heating or hot water. The amount of biomass used has been treated as a constant value in all our simulations and is not a subject of optimization. The cost has been assumed to be 50 € per MW h ([66]—the average value of biogas today is 60 €/MW h).

4.5.5. Import/export of electricity

In 2010 Germany exported 59.9 TW h of electricity and imported 42.2 TW h [19]. It may be an interesting option to increase electricity import and export with other countries within the European electricity network in the future. This will, in particular, be the case when overproduction in one country corresponds with shortages in other countries (or vice-versa) due to different weather conditions or other factors influencing demand or the production by fluctuating renewable energy sources. In general, exchange will be of high interest if other countries are able to provide large long-term storage capacities (e.g. Austria, Norway). However, it is very difficult to assess how much future energy systems can rely on the import and export of electricity because the underlying market models and price policies are unknown. Therefore we implemented the import and export of electricity in a simple way in the REMod-D model by defining a maximum capacity of electricity that can be imported. In cases where the electricity production from renewable sources and centralized combined heat and power systems falls below the actual electricity needs electricity is imported up to the pre-defined maximum value. Only in cases where still not enough electricity is available to satisfy the load combined cycle power plants are employed. A sensitivity analysis allows assessing the impact of this operation strategy on the optimal sizing of key components and in particular on long-term storage components such as the power-to-gas, gas storage and combined cycle subsystem.

4.5.6. Fossil fuels

To determine the composition of energy systems for the electricity and heat sector of Germany when less than 100% is supplied by renewable energy sources, the REMod-D model was extended to include a fraction of fossil fuels. We assume that fossil fuels are only used in combination with conversion processes with a high thermodynamic efficiency, i.e., for instance no classical boilers for burning fossil fuels for heating and hot water were implemented but rather gas heat pumps. We fix the amount of fossil fuels at the beginning of a simulation and then let the program determine the optimal composition of all converters.

5. System simulation, operation and control

The core of the REMod-D model is the calculation of an hourly energy balance of the German energy system according to the topologies shown in Fig. 3.1. This calculation is repeated for 8760 h (or one year). The calculation for the total year is repeated in a first loop until the centralized heat storage has a similar temperature at the beginning and the end of annual simulation. A second loop is implemented in order to determine the required capacity of

photovoltaic[4] converters in order to assure that the filling of the gas storage has the same value at the beginning and the end of the year, i. e., the criteria of an annual neutral energy balance is fulfilled. Then the total annual cost related to this composition of the energy system is calculated (see Section 6). Fig. 5.1 shows a flowchart of such a simulation step for a pre-defined set of all parameters, i.e. sizes of all components.

The models of all single components were described in Section 4. Here we describe the sequence of calculating the hourly energy balance depending on the actual conditions. The general concept of the operation follows the strategy always to prefer the conversion which assures highest thermodynamic efficiency. The next conversion option with next highest level of thermodynamic efficiency is only accepted if the conversion in the previous level is no longer possible due to limited capacity of converter or storage.

5.1. Heat sub-systems

The approach for treating heat sub-systems is explained in Fig. 5.2. It has to be noted that four different technical systems are installed to cover heat loads of the total building sector, namely electrical heat pumps, gas heat pumps, decentralized combined heat and power (dCHP) and centralized combined heat and power (cCHP). Solar thermal collectors can be used in addition but will not be able to supply 100% of the heating and hot water demand and are therefore treated separately. In a single simulation the share of the total building sector supplied with either technology is fixed. The sum of the shares of all four technologies has always to be 1:

$$f_{\text{el HP}}+f_{\text{GHP}}+f_{\text{dCHP}}+f_{\text{cCHP}}=1 \tag{9}$$

For solar thermal collectors we treated solar collectors installed in combination with centralized CHP and district heating networks separately from solar collectors installed in buildings with decentralized heating systems. Thus, in a single simulation the solar thermal collector area installed in combination with district heating, $A_{\text{coll,centralized}}$, has a fixed value and the solar collector area installed in all decentralized heating systems, $A_{\text{coll,decentralized}}$, has a fixed value. The distribution of the solar thermal collector area among the three ensembles of the building sector using decentralized heating systems is the same as for the heating technologies themselves, thus:

$$A_{\text{coll,decentralized}}=A_{\text{coll,el HP}}+A_{\text{coll,GHP}}+A_{\text{coll,dCHP}} \tag{10}$$

with

$$A_{\text{coll, el HP}}=f_{\text{el HP}}\times A_{\text{coll,decentralized}}, \tag{11}$$

$$A_{\text{coll, GHP}}=f_{\text{GHP}}\times A_{\text{coll,decentralized}} \quad \text{and} \tag{12}$$

$$A_{\text{coll, dCHP}}=f_{\text{dCHP}}\times A_{\text{coll,decentralized}} \tag{13}$$

In each sub-system two main cases have to be distinguished depending on whether the actual solar heat generation, $P_{\text{gen,sol}}$, exceeds or falls below of the actual heat load of the particular sub-system.

5.1.1. Electricity sub-system

The approach for treating the electricity sub-system is explained in Fig. 5.3.

Here, the first step is to calculate the total electrical hourly load, $P_{\text{load,el,tot}}$, which is composed of the electric load by non-energy applications, $P_{\text{load,el}}$, and the electricity needed to operate electrically driven heat pumps, $P_{\text{el, el HP}}$:

$$P_{\text{load,el,tot}}=P_{\text{load,el}}+P_{\text{el, el HP}} \tag{14}$$

The next step is to calculate the total electricity generation, $P_{\text{gen,tot}}$, from all renewable energy sources, i.e. offshore wind, $P_{\text{wind,offshore}}$, onshore wind, $P_{\text{wind,onshore}}$, photovoltaics, P_{PV} and hydro power, P_{hydro}, and by decentralized and centralized CHP, $P_{\text{el,dCHP}}$ and $P_{\text{el,cCHP}}$, respectively, in case they are needed to cover heat loads (see heat sub-system) and thus produce electricity.

$$P_{\text{gen,tot}}=P_{\text{wind,offshore}}+P_{\text{wind, onshore}}+P_{\text{PV}}+P_{\text{hydro}}+P_{\text{el,dCHP}}+P_{\text{el,cCHP}} \tag{15}$$

Two main cases have to be distinguished depending whether the actual generation, $P_{\text{gen,tot}}$, exceeds the actual load, $P_{\text{load,el,tot}}$ or $P_{\text{gen,tot}}$ falls short of $P_{\text{load,el,tot}}$.

6. Optimization methodology and computational performance

In the previous section the simulation of a single step, i.e. with given values of the size of all components, was described in detail. In this section, the optimization methodology and the corresponding computation performance are presented.

6.1. Calculation of annual total cost

After finishing a single simulation, the corresponding overall annual cost, $C_{\text{annual,tot}}$, is determined for an energy system with given values of the size of all components. This cost is calculated using the following equation:

$$\begin{aligned} C_{\text{annual,tot}} = & \sum_{i=1}^{N}\left[C_{\text{spec},i}\times P_i\times\left(\frac{1}{t_i}+m_i\right)\right] \\ & -\left[C_{\text{spec,ref,heat,centr}}\times P_{\text{load,heat, max ,centr}}\left(\frac{1}{t_{\text{ref,centr}}}+m_{\text{ref,centr}}\right)\right] \\ & -\Big[C_{\text{spec,ref,heat,decentr}}\times P_{\text{load,heat, max ,decentr}} \\ & \times\left(\frac{1}{t_{\text{ref,decentr}}}+m_{\text{ref,decentr}}\right)\Big] \\ & +\left[Q_{\text{heat,spec,rel}}\times C_{\text{esbr}}\times A_{\text{build,tot}}\left(\frac{1}{t_{\text{ref,esbr}}}+m_{\text{ref,esbr}}\right)\right] \\ & +[E_{\text{biomass}}\times p_{\text{biomass}}]+[E_{\text{fossil}}\times p_{\text{fossil}}] \\ & +\left[E_{\text{el,import}}\times p_{\text{el,import}}\right]-\left[E_{\text{el,export}}\times p_{\text{el,export}}\right] \end{aligned} \tag{16}$$

The meaning of the different lines in Eq. (16) is:

Line 1: Each summand with index '*i*' in the sum in the first line of Eq. (16) corresponds to the annual cost of each component of the energy system described Section 4. These components are:

- Electricity generation: offshore wind converters, onshore wind converters, photovoltaic systems, hydro-power stations.
- Heat generation: solar thermal collectors connected to district heating systems, decentralized solar thermal collectors.
- Conversion: power-to-gas converters, combined cycle power plants, centralized combined heat and power systems, decentralized combined heat and power systems, electrically driven heat pumps, gas driven heat pumps.
- Storage: batteries, pumped hydro-power storage, centralized heat storage devices.
- Grids: electricity grids, district heating networks.

$C_{\text{spec},i}$ denotes the specific cost of this component, P_i the installed capacity (power, energy content or area, respectively), t_i the lifetime

[4] We used the size of photovoltaic systems for equalizing the annual energy balance. Reason is that the technical potential for photovoltaics is less limited than that for onshore wind and offshore wind. More details about technical potentials for renewable energy sources are described in the second part of this paper [3].

and m_i the O&M cost (percentage of investment cost). All values were specified in Section 4.

Line 2 and line 3: In the second and third line of equation 15, the cost for reference heating technologies in both the centralized and decentralized case, respectively, is subtracted. This cost would be necessary also in a completely fossil fuel based heating sector using state-of-the-art technology. Thereby only the extra cost of high efficient systems (electric heat pumps, gas heat pumps, combined heat and power systems) compared to standard heating technology (condensing gas boilers) is taken into consideration for calculating the total annual cost.

Line 4: The fourth line refers to energy saving building retrofit (abbreviated 'esbr '). $Q_{heat,spec,rel}$ is the average specific heating demand of the building stock given as a percentage of the base value (2010) and C_{esbr} the corresponding specific cost of energy saving building retrofit (see Fig. 4.1). $A_{build,tot}$ is the total heated floor area of the building stock (see Section 4.1).

Line 5: In line 5 the cost of biomass is calculated. $E_{biomass}$ is the annual energy amount of used biomass and $p_{biomass}$ the cost per unit. Since there are manifold different production technologies to produce gaseous or liquid biomass, no single technology and their corresponding cost parameters has been considered but an average price of biomass is taken. In a similar way the cost of fossil fuel is calculated in the case of scenarios allowing the use of fossil fuel.

Line 6: In line 6 the cost and revenues for import and export of electricity is calculated based on the amount of imported electricity, $E_{el,import}$, and related average cost, $p_{el,import}$ and the amount of exported electricity, $E_{el,export}$ and the corresponding revenue, $p_{el,export}$.

6.2. Optimization methodology

The optimization process is based on a modified multi-dimensional *regula falsi* approach. Basics of the underlying mathematics and numerical solution can be found in standard textbooks (e.g. [67]).

In this approach, a minimum and maximum possible value, ν_{min} and ν_{max}, has to be pre-defined for each parameter which is subject of optimization, i.e. a parameter range is defined. In most cases we chose zero as the minimum value. The maximum value was chosen to be at the reasonable maximum capacity of that particular component. For the overall heating energy demand of the building sector we chose 20% of the 2010 level as the minimum value. Any lower heating energy demand would be unrealistic.. In a first iteration loop for each parameter subject to optimization, annual simulations are carried out with two values, namely with a first lower value ν_1 and with a second larger value ν_2:

$$\nu_1 = \nu_{min} + (1/m) \times (\nu_{max} - \nu_{min}) \quad \text{and}$$
$$\nu_2 = \nu_{min} + ((M-1)/M) \times (\nu_{max} - \nu_{min}) \tag{17}$$

We worked with different values of m, e.g. $m=3$, $M=4$ and $M=10$ and compared the results. The smaller the value of M, the closer the chosen values of the particular parameter are to the mid value of the parameter range. Vice versa, the larger the value of M, the closer the chosen values of the particular parameter are to the boundary of the parameter range. Combination of N values that are subject of optimization leads to 2^N single simulations per iteration loop. In simulating the "100% scenario", we have 11 free parameters that are subjects of optimization and thus $2^{11}=2048$ single simulations are carried out. For each of the single simulations the total annual cost is computed.

After the first iteration loop has been finished, the parameter set leading to the minimum of the total annual cost is determined. Then, for each parameter subject to optimization, the parameter range is reduced. In case the value ν_1 of parameter i was the one which led to the minimal total annual cost, the minimum of the parameter range, ν_{min}, remains unchanged and the new maximum of the parameter range is reduced according to:

$$\nu_{min\ ,new} = \nu_{min\ ,old} \quad \text{and}$$
$$\nu_{max\ ,new} = \nu_{min\ ,old} + L/(L+1) \times (\nu_{max\ ,old} - \nu_{min\ ,old}) \tag{18}$$

In case that value ν_2 of parameter i was the one which led to the minimal total annual cost, the minimum of the parameter range, ν_{min}, is increased in a corresponding way and ν_{max} remains unchanged. Again, we carry out the simulations with different values of L, e.g. $L=3$, $L=10$ and $L=100$. The larger L is, the lower the reduction of the parameter space is from one iteration loop to the next. Thus, with a large value of L, more iteration steps are required in order to achieve the same reduction of the parameter space achieved with a smaller value of L. If, for instance, L is set to 3, the parameter range is reduced by a factor of 2/3 for each parameter subject to optimization in each iteration. After K iteration loops, the parameter range has been reduced to $(2/3)^K$. With $K=12$ iteration loops, the final parameter range equals about 0.771% of the initial parameter range for each parameter which is subject of optimization. Fig. 6.1 shows an example of the overall results of the optimization. Each dot represents one specific cost value, calculated with one specific set of parameters for a single simulation of a whole year. During the optimization process several thousands sets of parameters are calculated and compared by means of the specific total annual cost value. It is evident how the iteration loops converge and that the differences between different parameter sets are marginal in the final iteration loop.

6.3. Computation performance

We applied the modified multi-dimensional *regula falsi* method because it proved to be robust. On a normal state-of-the-art PC, the complete calculation of a 100% scenario with 11 parameters to be optimized and 50 iteration loops (programmed in Delphi[5]) takes about 8 h. One of the results identified during carry-out of many simulations with changed numerical parameters (M and L of the previous section) and modified parameter ranges for components was that many local minima exist, which lead to similar values of the goal function, i.e., total annual cost. More details are presented and discussed in the second paper [3].

7. Summary and outlook

In this paper we describe a novel modeling approach for simulating the electricity and heat sector of a potential future German energy system based on 100% renewable energies (or a high penetration thereof). The model uses simple models for the single components. The interaction between the different components and all related energy flows are simulated in detail on an hourly basis for a complete year. An efficient and robust optimization method has been developed which allows many simulations to be performed within a realistic running time. As a result, comprehensive sensitivity studies can be carried out and a wide range of parameter variations can be implemented. With this tool, favorable combinations of components implemented in future energy systems using a high share of renewable energies can be determined. The simulation results are intended to help decision

[5] www.embarcadero.com.

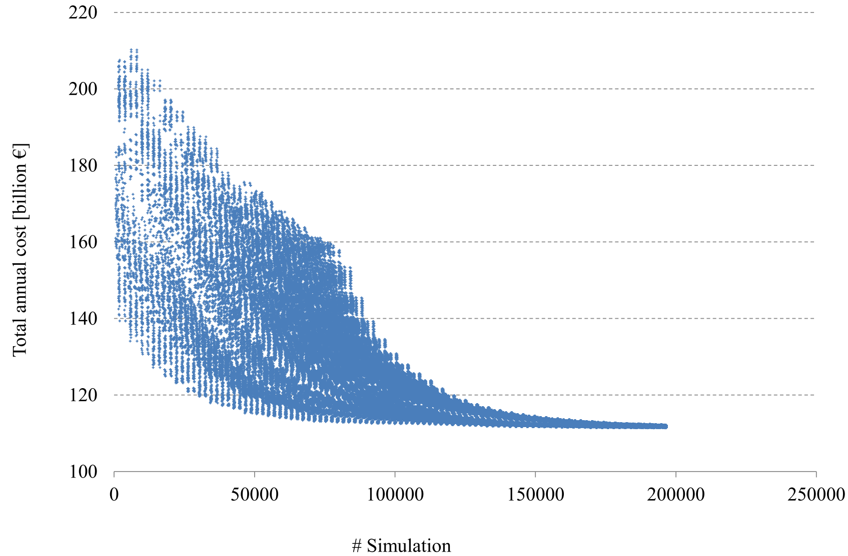

Fig. 6.1. Example of a complete simulation. Each dot refers to the annual cost of a single simulation corresponding to a set of parameters during the optimization procedure.

makers in policy and the energy economy sector to identify robust scenarios and assess related total annual costs of the future energy system. In the second part of this paper we describe first results obtained from the model.

The chosen optimizing algorithm is very robust. Nevertheless, it cannot be assured that the absolute minimum of the multi-dimensional parameter space is tracked. We carried out various simulation runs using different numerical parameters (parameters spaces for the different components, numerical parameters L and M described in Section 6). The results showed very similar total annual costs with different compositions of the component size. This indicates that many local minima exist. Interpretation of the results leads to the conclusion that various system solutions are possible which lead to almost the same total annual cost. Thus, other than techno-economic criteria may be taken into consideration for the design of future energy systems with a very high share of renewable energy sources.

Various plans exist to further expand the broadness and the detail in the tool. On the one hand, we plan to include the mobility and analyze, for instance, the impact of different concepts of private mobility (e.g. battery based versus hydrogen based or a mix of both) on the overall energy system. Also the industrial sector, (i.e. fuel based industrial processes, which are not yet covered in the recent REMod-D model) shall be implemented, at least on an annual balance. In particular, the building sector will be modeled in more detail e.g. by including building thermal mass as a means to store energy and thus enabling load shifting and storage for fluctuating renewable energy sources. Also the typology of the building sector shall be represented in more detail, e.g. distinguishing between different building types and building energy standards and the various cost functions for considering the extra costs associated with an energy retrofit. Our aim is that the model can be applied in more detail for the building sector and used to compare different measures in the different sectors of the building stock.

In order to increase the usefulness of the model not only in the description of target compositions of the energy system but also pathways to get there, we plan to implement a methodology which allows to model and analyze intermediate steps between the today's situation and the target system.

Finally the model can be applied to other regions or countries. This will be more straightforward for countries or regions which have a climate similar to Germany. For regions or countries in other climatic zones, adjustments have to be made. For instance, regions in the earth's Sun Belt have a much lower heat demand and higher cooling demand. Also in these locations, other technologies such as concentrating solar power CSP may be an important option for electricity production and will have to be implemented.

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